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A Computer-based Model for Design Rainfall in the United Kingdom

by J. F. KEERS, B.Sc. and P. WESCOTT

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85p net

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U.D.C. 551.577.37(41.4):681.3

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ISBN 0 11 400298 3

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A Computer-based Model for Design Rainfall in the United Kingdom

By J. F. Keers, B.Sc. and P. Wescott

SUMMARY

This paper describes a computer-based model suitable for determining rainfall depth-duration-frequency statistics for any location in the United Kingdom. Point or areal storm events for drainage or engineering design purposes may be computed. The model uses the techniques recommended in Volume 2 of the *Flood Studies Report* and the mapped tabular rainfall data contained therein. The model allows for a variety of computer-produced output aimed at meeting the needs of different users.

1. INTRODUCTION

Rainfall statistics describing the relationship between depth, duration, and frequency of occurrence of extreme rainfall are required for engineers to optimize the design of schemes for water resources, river management and drainage (including urban storm-water sewers). With the publication of the *Flood Studies Report* (1975) – containing Meteorological Studies in Volume 2, hereafter referred to as *FSR*(2) – engineers are now able to determine a design rainfall for almost any specific problem. *FSR*(2) was produced by a small team led by A. F. Jenkinson and it describes the analysis techniques used and gives examples of the methods of calculating design rainfalls of various durations and return periods for any point location or area in the British Isles. However, the computation of design rainfalls is often a tedious and time-consuming task if carried out by hand-and-eye methods using the tables and maps of rainfall parameters provided in the *Report.* Thus there is a requirement for a computer-based method for calculating design rainfalls, particularly if rainfalls are required for several durations and return periods for a catchment area or for several point locations.

The authors have developed computer programs to provide suitable output for a variety of users of rainfall statistics. These programs have been used operationally since early in 1975 (by the hydrometeorological enquiry section of the Meteorological Office) to answer an increasing number of requests for design rainfalls.

2. COMPUTER MODEL

2.1. *Outline of method*

The Meteorological Office computer programs are based on *FSR*(2) which utilizes basic maps to derive 5-year values of rainfall, that is to say values which are reached or exceeded once in five years on average, for durations of 60 minutes, two days* and 25 days at any

*In this paper a day refers to a rainfall day which is the specific 24-hour period from 0900 to 0900 GMT on the following day.

point location. The 5-year rainfalls of other durations are then determined by interpolation or extrapolation from the rainfalls which have been extracted from these three basic maps. The rainfalls for other return periods are next computed using a model relationship, which is given in *FSR*(2), between the 5-year value and the values for other return periods. This relationship is assumed to be the same for all locations in England and Wales and a slightly different relationship is used for Scotland and Northern Ireland.

2.2. *Standard maps*

The mapped data provided in *FSR*(2) are stored in the computer in the form of grid-point values at three-and-one-third kilometre intervals covering the United Kingdom. The maps are of the following fields of rainfall:

(a) 60-minute rainfall with return period 5 years.
(b) 2-day rainfall with return period 5 years.
(c) 25-day rainfall with return period 5 years, expressed as a percentage of the 1941–70 average annual rainfall.
(d) Annual average rainfall (1941–70).
(e) Estimated maximum 2-hour rainfall.
(f) Estimated maximum 24-hour rainfall.

The grid-point values, 46 000 for each field, were extracted by hand, punched on computer cards and, after checking, stored on direct-access data sets on IBM disc. Thus basic rainfall data for any grid point can be speedily accessed.

The *FSR*(2) maps used for manual extraction of the grid-point data were not presented in enough detail to determine uniquely the value extracted manually at some grid points. Therefore some additional analysis of the data was carried out.

2.3. *Determination of 5-year rainfalls*

For a particular location, the rainfall with return period 5 years and of any specified duration can be computed by interpolation, or extrapolation, using the 60-minute, 2-day and 25-day (5-year) rainfalls. These are derived for the particular location from the grid-point data sets using a linear interpolation scheme based on the four surrounding grid-point values.

The rainfall values of return period 5 years for durations between 1 minute and 2 days are computed by means of the following equation from *FSR*(2) which relates the rainfall intensity (I) and duration (D) in hours:

$$I = I_0 (1 + BD)^{-n} \quad \ldots (1)$$

where I_0, B and n are parameters which may vary with geographical location. The model is relatively insensitive to variations of B, therefore a constant value, $B = 15$, is taken.

Equation (1) can be written:

$$\log I = \log I_0 - n \log(1 + 15D) \quad \ldots (2)$$

from which it can be seen that a graphical plot of $\log I$ against $\log (1 + 15D)$ is a straight-line relationship with gradient $-n$. For a particular location $-n$ and I_0 can be determined by fixing two points on the straight-line relationship and the mapped values of 60-minute

and 2-day (5-year) rainfalls are used to determine uniquely the solution of equation (2). The formulae for interpolation or extrapolation for 5-year rainfalls of any duration up to 48 hours can then be written as in Table I (i), where the 48-hour rainfall is related to 2-day rainfall by the equation in Table I (ii).

TABLE I. *Formulae for determining 5-year rainfall M_5 in millimetres for specified durations less than 25 days*

Equation No.	Range of duration (D) hours	Formula
i	$D < 48$	$\log M_{5,(D)} = D\log(A_{48}/48) + D \log (721/1+15D) \log(48A_1/A_{48})/\log (721/16)$
ii	$D = 48$	$M_{5,(48)} = 1.06\, B_2$
iii	$48<D<72$	$\log M_{5,(D)} = \log A_{72} - \log(72/D)\log(A_{72}/A_{48})/\log(72/48)$
iv	$D = 72$ ($\bar{R}_A > 14$)	$M_{5,(72)} = (1.191 + 0.00116\bar{R}_A)B_2$
v	$D = 72$ ($\bar{R}_A \leqslant 14$)	$M_{5,(72)} = (1.127 + 0.00623\bar{R}_A)B_2$
vi	$72<D<96$	$\log M_{5,(D)} = \log A_{96} - \log (96/D)\log(A_{96}/A_{72})/\log(96/72)$
vii	$D = 96$ ($\bar{R}_A > 14$)	$M_{5,(96)} = (1.330 + 0.00295\bar{R}_A)B_2$
viii	$D = 96$ ($\bar{R}_A \leqslant 14$) days	$M_{5,(96)} = (1.181 + 0.01541\bar{R}_A)B_2$
ix	$4<D<25$	$\log M_{5,(D)} = \log B_{25} - \log(25/D)\log(B_{25}/B_4)/\log(25/4)$

Notes: A_x denotes 5-year rainfall of duration x hours.
B_x denotes 5-year rainfall of duration x days.
$\bar{R}_A$ is average annual rainfall (AAR) in hundreds of millimetres.

The application of the method for two different locations is illustrated in Figure 1. One location (Bala, North Wales) has a high average annual rainfall and a correspondingly high value of 2-day (5-year) rainfall associated with relatively low values of short duration (less than 30 minutes) rainfall as indicated by line (b) in Figure 1. This is in accordance with our physical understanding of rainfall in mountainous regions of the United Kingdom where frontal or cyclonic rainfalls are often enhanced, but extreme summer thunderstorms are less likely to occur. The other location, line (a) in Figure 1, is London, where the 2-day (5-year) rainfall is relatively low and the short-duration rainfalls are relatively high. The 60-minute (5-year) rainfall varies only about ±15 per cent around a mean

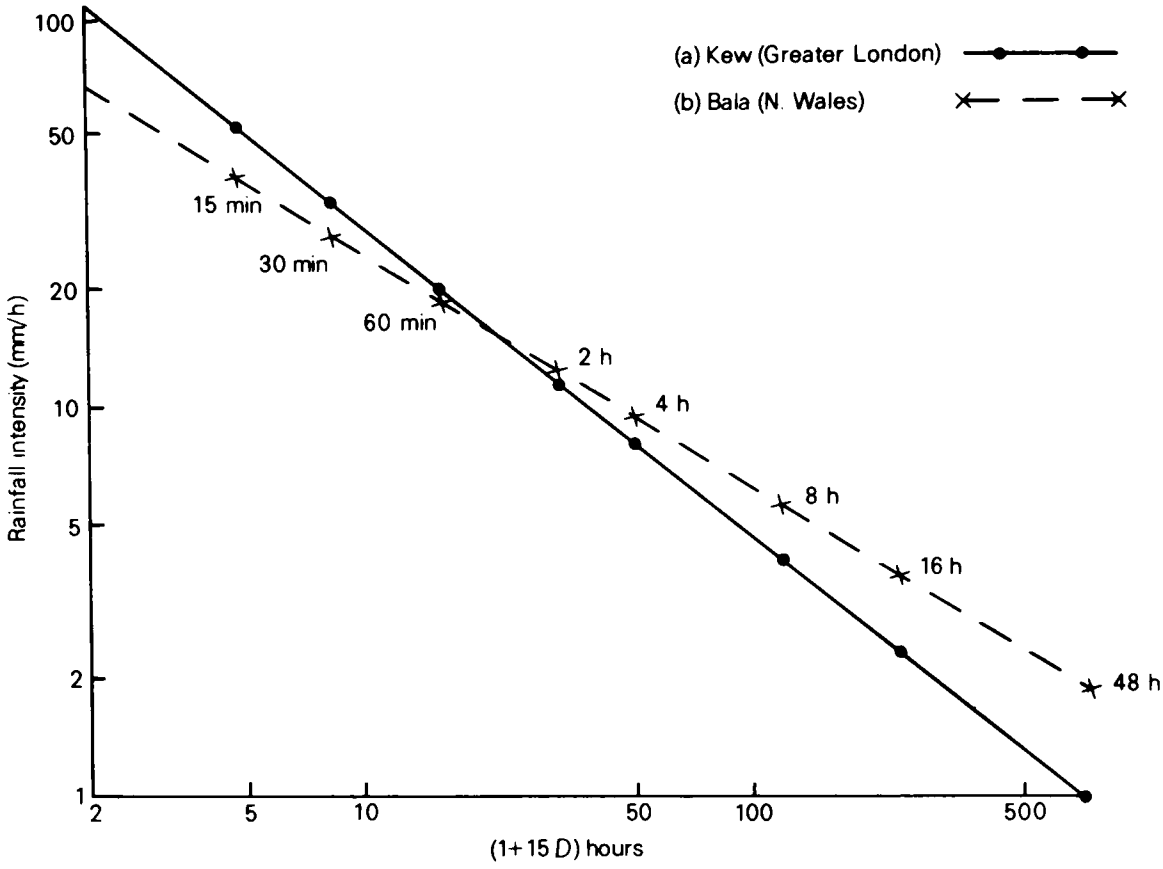

FIGURE 1. *Relation of rainfall intensity to duration for 5-year events*

value of 18.5 mm for 85 per cent of the United Kingdom, whereas the 2-day (5-year) rainfall is very important for determining the very short-duration rainfalls using the model relationship given by equation (1).

The interpolation formulae used to compute the 5-year rainfall of any duration between 48 hours and 25 days are given in Table I, equations iii to ix.

Equations iv, v, vii and viii of Table I were derived from the values, given in *FSR*(2), relating the 72-hour and 96-hour (5-year) rainfalls to the 2-day (5-year) and average annual rainfall. The best estimates of 5-year rainfall for durations from 48 to 72 hours, 72 to 96 hours, and 96 hours (four days) to 25 days, are obtained by linear interpolation on a diagram of log R against log D (where R and D are the 5-year rainfall and duration respectively), as recommended in *FSR*(2). The respective equations for these interpolations are given in Table I, equations iii, vi and ix.

2.4. *Determining rainfalls of any return period*

Section 2.3 describes the method of deriving 5-year rainfalls, denoted by M_5, of any specified duration for any location in the United Kingdom, using grid-point data from

maps of 60-minute, 2-day and 25-day rainfall with return period 5 years. The rainfall for any other return period T years, $T > 5$, denoted by M_T is computed using the *FSR*(2) model relationship between M_5 and M_T, namely:

$$\log (M_T/M_5) = C(\log(T - 0.5) - 1.5) \quad \ldots (3)$$

where C is a constant for a particular geographical location and the variation with rainfall duration is allowed for through its effect on the M_5 value. The value of C is assumed to be a function of the M_5 value, namely:

$$C = A_0 + A_1 M_5 + A_2 M_5^2 \quad \ldots (4)$$

where the coefficients are constants determined by the method of least squares for different ranges of M_5. The full range of possible M_5 values cannot be accurately related to C by means of just one equation as in equation 4, but a very accurate and practical solution was to derive different regression coefficients for different ranges of M_5 and these are given in Table II.

TABLE II. *Values of regression coefficients for use in Equation 4*

Region	Range of M_5	A_0 ($\times 10^{-4}$)	A_1 ($\times 10^{-6}$)	A_2 ($\times 10^{-9}$)
	millimetres			
England	0–10	1699	2800	114 000
	10–30	1644	5831	−13 430
and	30–75	2644	−1621	3 150
	75–150	2718	−1947	6 187
Wales	> 150	1454	−194	114
	0–13	1648	8330	−304 700
Scotland	13–25	2349	−771	−17 250
and	25–50	2502	−2109	12 130
N. Ireland	50–150	2274	−1208	3 220
	> 150	1460	−202	120

At a point location a 1-year rainfall of any specified duration may occur more than once, or maybe not at all, in a particular year. This is due to the natural variation from one year to another of meteorological situations leading to extreme rainfall. Therefore a return-period analysis of rainfall based on 'annual maxima' values only, as opposed to a count of the frequency of rainfalls above specified thresholds, will not always produce the best results. Annual maxima rainfalls are well suited for the application of the theory of extreme-value analysis (Jenkinson, 1975) but in general for return periods less than 5 years best results are achieved by methods based simply on counting the number of occasions when rainfall reached or exceeded specified thresholds. Jenkinson, in *FSR*(2), related the twice-a-year, once-a-year, and once-in-two-year rainfalls to a corresponding once-in-five-year rainfall and the relationships, presented in Table III, are used in the computer program.

TABLE III. *Twice-a-year, 1-year and 2-year rainfalls expressed as a percentage of 5-year rainfall*

	England and Wales			Scotland and N. Ireland		
M_5	Twice-a-year	1-year	2-year	Twice-a-year	1-year	2-year
mm						
0.5	52	68	81	55	68	81
2	49	65	79	55	68	81
5	45	62	77	54	67	81
10	43	61	75	55	68	80
15	46	62	75	55	69	80
20	50	64	77	56	70	81
25	52	66	78	57	71	82
30	54	68	80	58	72	83
40	56	70	82	59	74	84
50	58	72	84	60	75	85
75	63	76	86	62	76	86
100	64	78	88	63	78	88
150	64	78	89	64	79	89
200	64	78	89	65	80	90
500	65	79	90	66	80	91
1000	66	80	91	66	80	91

If the return period of a particular rainfall is 2 years when derived from a 30-year record, say, then the return period over any 10-year period or 5-year period of the same 30-year record may be significantly different; a standard deviation of 15 per cent is typical. Therefore if a depth–duration–return-period analysis is made of a rain-gauge record, rather than by means of the *FSR*(2) or a computer model based on the *FSR*(2), an apparent discrepancy in design rainfalls will result unless the rain-gauge data are representative of rainfall in the area, reliable, and of 20 or more years of record. In *FSR*(2) care was taken to use only data which gave results which were considered acceptable, and data from many recording rain-gauge stations in particular were thereby excluded.

2.5. *The estimation of maximum precipitation*

Jenkinson in *FSR*(2) derives estimates of the maximum rainfall for any specified duration by a physical approach which contrasts with statistical methods used by workers such as Herschfield (1961). Jenkinson's method utilizes the greatest observed storm efficiency, that is the ratio of rainfall amount to water availability in a vertical column, of any storm for which data were available. The efficiency of other extreme storms in different parts of the country was maximized to estimate the maximum rainfall. The geographical distributions of estimated maximum 2-hour and 24-hour precipitation were

TABLE IV. *Estimated maximum rainfall for some durations less than 2 hours, expressed as a percentage of the 2-hour value*

Duration	Range of Average Annual Rainfall ($\bar{R}_A$) in millimetres		
	$\bar{R}_A < 1400$	$1400 \leqslant \bar{R}_A < 2800$	$2800 \leqslant \bar{R}_A$
minutes			
1	6	6	6
2	11	11	10
5	23	22	21
15	47	45	43
30	65	62	59
60	83	79	75

TABLE V. *Estimated maximum rainfall for durations longer than 24 hours, expressed as a percentage of the 24-hour value*

Duration	Range of Average Annual Rainfall ($\bar{R}_A$) in millimetres							
	500–600	600–800	800–1000	1000–1400	1400–2000	2000–2800	2800–4000	4000
hours								
48	110	110	110	111	112	114	120	123
72	113	113	114	116	118	123	131	135
96	117	117	118	120	124	132	142	148
days								
8	124	125	128	135	149	162	179	187
25	148	154	168	192	220	249	289	309

determined and were mapped (see section 2.2). Maxima for a selection of durations less than 2 hours were estimated as a percentage of the 2-hour maxima (see Table IV) by analysing extreme rainfalls of various durations. The estimated maxima for durations between 24 hours and 25 days were estimated as a percentage of the 24-hour maxima (see Table V). The estimated maxima for durations between 2 hours and 24 hours are determined by linear interpolation on a diagram of rainfall against the logarithm of the duration.

2.6. *Point to area rainfall relationship*

The rainfall depth–duration–return-period relationships presented in the previous sections of this paper all refer to point rainfalls, that is rainfall at a specific location, since they all derive from rain-gauge measurements. Invariably the engineer requires information on areal rainfall rather than on point rainfall where the area may be the drainage area of an electricity generating station, an urban area, or a large river catchment.

Obviously the N-year rainfall for an area will be less than the N-year rainfall at a point, and the greater the area the more the point rainfall must be reduced. The reduction factor is commonly called an areal reduction factor (ARF). The data show conclusively that the greater the rainfall duration the less the point rainfall needs to be reduced.

Every rainfall event affects an area rather than a point and the area–depth relationship is different in every case. *FSR*(2) presents a statistical relationship between N-year point rainfalls and N-year areal rainfall events, where the geographical differences are accounted for by the differences in point-rainfall values.

The ARF used is based on *FSR*(2) values and is mathematically modelled by relating the ARF with the size of the catchment area and the rainfall duration according to the following equation:

$$F = 1 - bD^{-a} \qquad \ldots (5)$$

where F is the areal reduction factor, D is duration in hours, and a and b are functions of area A (km^2). The optimum values for a and b, given in Table VI, were chosen by trial-

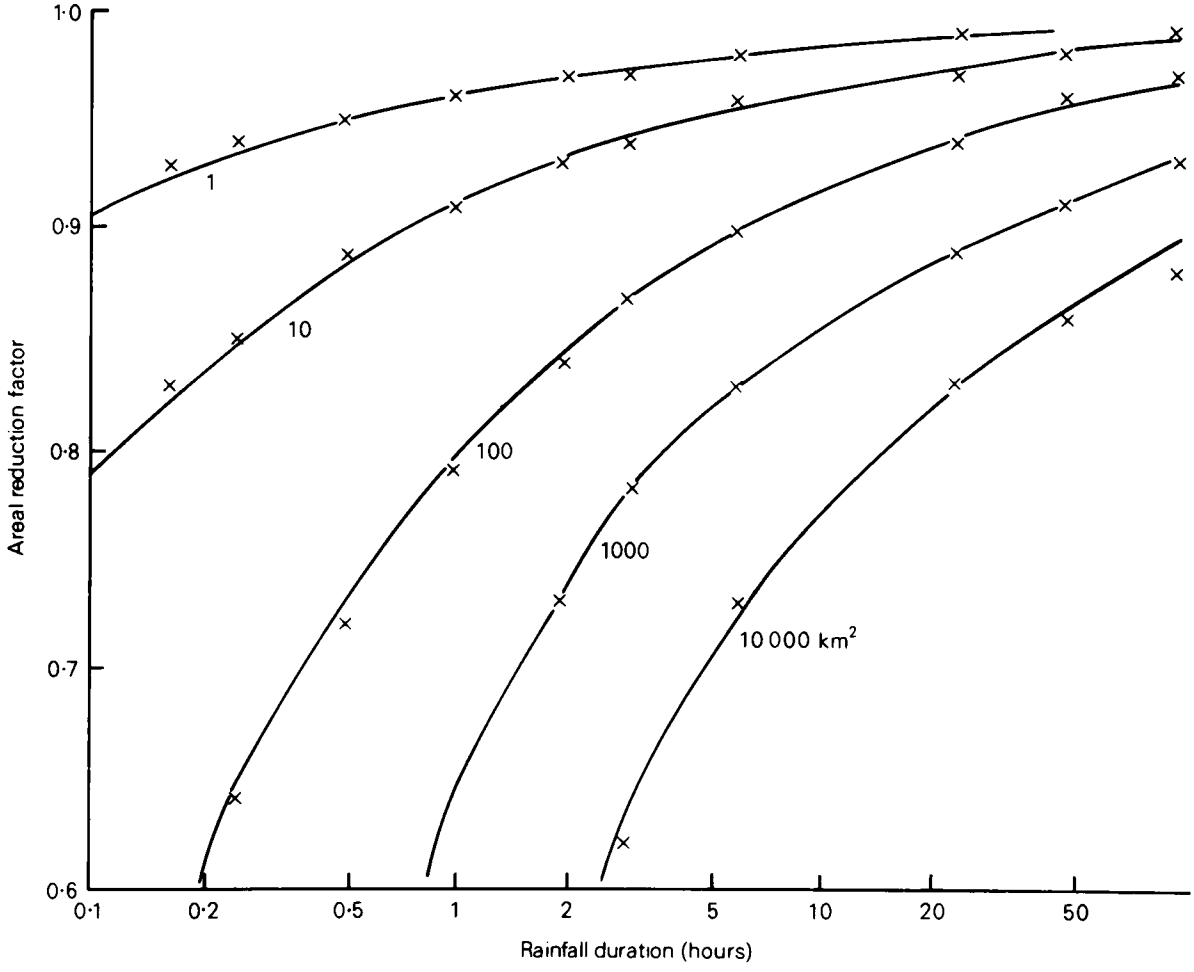

FIGURE 2. *Areal Reduction Factor versus rainfall duration for areas of different size*

TABLE VI. *Areal reduction factor coefficients for use in Equation 5*

No.	Size of Area A(km^2)	a	b
1	$A \leqslant 20$	$0.40 - 0.0208 \log (4.6 - \log A)$	$0.0394\, A^{0.354}$
2	$20 < A < 100$	$0.40 - 0.00382\, (4.6 - \log A)^2$	$0.0394\, A^{0.354}$
3	$100 \leqslant A < 500$	$0.40 - 0.00382\, (4.6 - \log A)^2$	$0.0627\, A^{0.254}$
4	$500 \leqslant A < 1000$	$0.40 - 0.0208 \log(\log A - 4.6)$	$0.0627\, A^{0.254}$
5	$1000 \leqslant A$	$0.40 - 0.0208 \log(\log A - 4.6)$	$0.105\ A^{0.180}$

and-error methods and the goodness of fit is illustrated in Figure 2 where the *FSR*(2) values are compared with the values obtained from equation 5.

Thus areal rainfall estimates can be derived from the comprehensive statistics of point rainfall. An alternative approach using only areal rainfall factors to investigate areal rainfall statistics is not justified in view of the relatively limited data on extreme areal rainfall events compared with point-rainfall measurements in some parts of the United Kingdom. Also the spatial variability of rainfall is such that in many instances areal rainfall cannot be adequately measured from the existing network of rain-gauges.

2.7. *Storm profiles*

Storm rainfall rarely falls for long at a uniform intensity. A profile of rainfall intensity versus time, as in Figure 3, is commonly referred to as a storm profile. For flood-alleviation design purposes the storm profile is important because for a specified duration and total rainfall the storm with the greatest peak intensity, that is to say the sharpest profile, will often result in the greatest peak flow in the drainage system.

For a given storm duration and total rainfall there is clearly an infinite variety of storm profiles. The range of variation is related to the different rainfall types; for example very sharp storm profiles of short duration (less than 2 hours) are usually associated with convective-storm rainfall, whereas flatter profiles result from more continuous and less intense rainfall processes, for example warm front rain. The speed of movement of a rainfall system across a point or area and the local development and decay of rainfall intensity contribute to the shape of the storm profile. The research carried out in the Meteorological Office on storm profiles (*FSR*(2)) included the frequency of occurrence of profiles of varying degrees of sharpness. The unit used to express profile sharpness is the percentile; for example, a profile which is not exceeded in terms of sharpness on 90 per cent of occasions is referred to as the 90-percentile profile. A range of storm profiles all giving the same total rainfall in a fixed duration are shown in Figure 3. The 50-percentile profile is the median profile. Figure 4 presents a range of 50-percentile profiles, which show that the shape of profile is a function of rainfall duration.

A design engineer is faced with some difficult problems if he wishes to use the results referring to the various shapes of the storm profile (for example how sharp should the storm profile be and what storm duration should be used?). In practice an engineer generally opts for a simplified design technique. An example is the storm-sewer design technique of the Transport and Road Research Laboratory at Crowthorne, Berks. (Road Research Laboratory, 1963) which utilizes a fixed-duration (2-hour) storm profile with

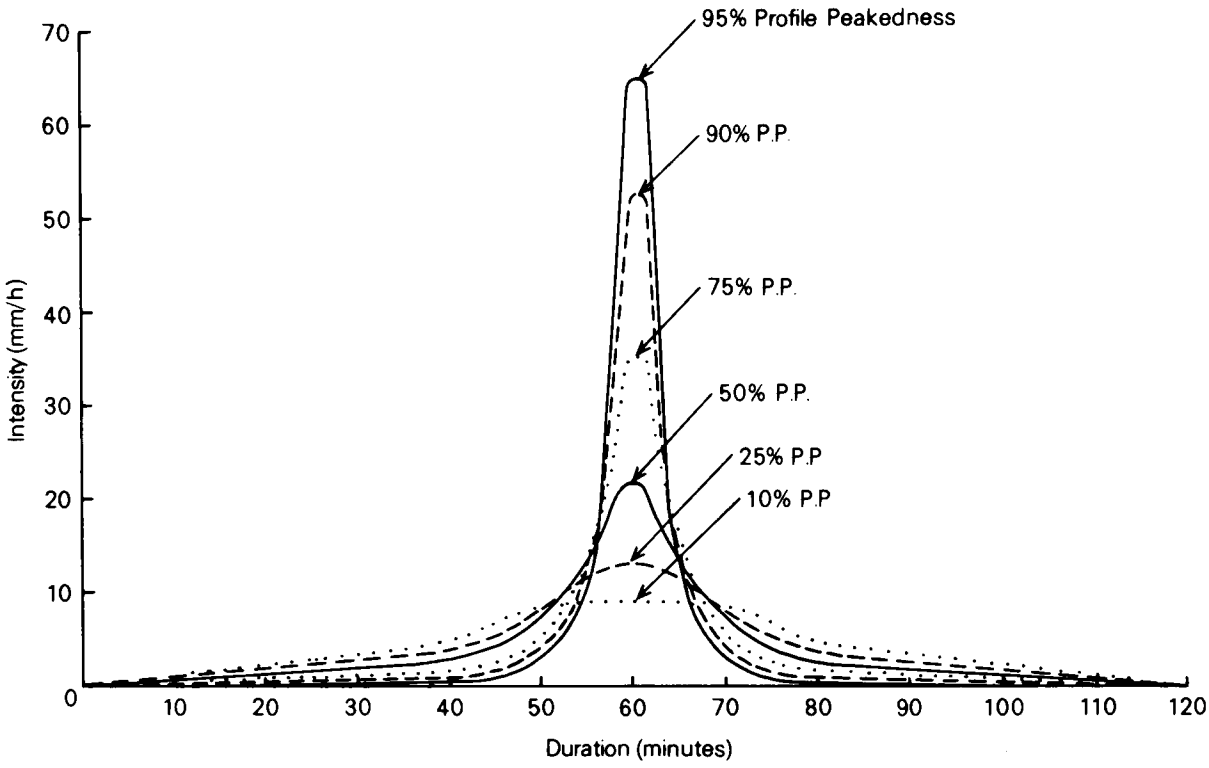

FIGURE 3. *Range of storm profiles (return period 2 years) for a fixed duration of 2 hours*

sharpness equivalent to a *FSR*(2) 75-percentile profile, that is to say, only exceeded in terms of sharpness by 1 in 4 storms. The total rainfall in the 2-hour period is varied according to the return period required, but no consideration is given to the probability of such a sharp storm profile occurring. Also there may be occasions when the optimum (resulting in the greatest peak flow) storm duration may be greater than 2 hours. However, the RRL (1963) storm profiles simplify rainfall input since their construction ensures that the one storm profile of specified return period is adequate for all pipe systems with a time of concentration (response time) of 120 minutes or less. This is because the *N*-year 10-minute rainfall is 'nested' in the *N*-year 15-minute rainfall which in turn is 'nested' inside the *N*-year 30-minute rainfall and so on, up to 120 minutes.

FSR(2) enables a design storm profile to be constructed to any predetermined specification and if the specification is not certain a variety of design storms can be constructed, all for a fixed return period. The optimum design storm can then be determined by experiment.

The Meteorological Office and the Transport and Road Research Laboratory carried out a series of experiments with different-shaped storm profiles for urban drainage design and concluded that there is a relationship between storm duration and the sharpness of the storm profile. In effect if a median summer-storm profile (50 percentile) is chosen, then the optimum storm duration is between two and three times the time of concentration: for example the 60-minute storm should be used for a drainage scheme with

time of concentration 20 to 30 minutes, but the pipes far upstream should be designed by the use of a storm of shorter duration or with mean rainfall intensities (section 2.4) applied by the Rational Design Method (Escritt, 1950).

In general, river catchments flood as a result of heavy rainfall over a period of hours, or even days, and the Institute of Hydrology, Wallingford in *FSR*(1) (1975) recommends that use be made in designs of a 75-percentile winter profile with the storm duration determined by catchment characteristics.

The computer-based model derives 50- and 75-percentile summer (May to October) or winter (November to April) storms of any specified duration. The return period of the storm profile is equated with the return period of the total rainfall in the central one-third of the total duration, which can be chosen to be the time of concentration of the drainage system. This method of rainfall input combines the principle of the Rational Design Method with the use of a median storm profile. The rainfall intensities for each minute of the design storm duration are computed using tabular data describing the particular percentile of profile as presented in *FSR*(2) and reproduced in more detail for the median summer and winter storm profiles in Table VII.

TABLE VII. *Median storm profiles for summer and winter storms*

Cumulative percentage duration about centre	Proportion of mean storm intensity	
	Summer	Winter
2	3.75	2.00
5	3.29	1.94
7	3.00	1.90
10	2.70	1.86
15	2.10	1.80
20	1.60	1.70
25	1.30	1.59
30	1.00	1.45
35	0.84	1.28
40	0.74	1.11
45	0.67	0.95
50	0.60	0.80
55	0.53	0.68
60	0.49	0.60
65	0.44	0.54
70	0.40	0.50
75	0.37	0.47
80	0.34	0.44
85	0.31	0.42
90	0.30	0.40

3. EXAMPLES OF APPLICATIONS OF THE COMPUTER-BASED MODEL

3.1. *Rainfall depth–duration–return-period relationships*

The computer program can output the rainfall in millimetres for a range of durations and return periods for a specified point or area in the United Kingdom. Unless otherwise required the output is for a standard range of durations and return periods from 1 minute up to 25 days (approximately equivalent to one calendar month) and from twice-a-year to the estimated maximum respectively. For a point, only the National Grid Reference number needs to be specified, whereas for an area the boundary should be drawn on an Ordnance Survey map, preferably to the scale 10 miles to the inch or a metric equivalent.

TABLE VIII. *Rates of rainfall at Bala (N. Wales) for specified durations and return period*

Duration	Return period						
	Years						
	1	2	5	10	20	50	100
minutes	*mm/h*						
2	50	61	78	89	102	120	136
5	38	47	61	71	81	96	109
10	29	35	47	54	63	75	87
15	24	29	39	45	53	64	74
30	17	21	27	32	38	46	54
60	11.8	14	19	22	26	32	37
90	9.5	11.4	15	17	21	25	30
120	8.2	9.7	12.4	15	17	21	25
hours							
4	5.6	6.6	8.2	10.3	11.3	13.8	16.0
6	4.5	5.3	6.4	7.5	8.7	10.6	12.2
12	3.1	3.6	4.2	4.9	5.6	6.7	7.6

TABLE IX. *Computer model calculation of areal – mean rainfall for the Wansbeck river catchment (area* 390 km^2) *and the equivalent Flood Studies Report results in brackets*

Return period	Duration				
	½h	2h	6h	24h	48h
Years	*millimetres*				
1	5.2 (5.1)	11.1 (11.2)	18.2 (18.2)	31.3 (31.3)	40.6 (40.9)
2	6.1 (5.8)	12.8 (12.3)	20.6 (20.1)	35.2 (34.4)	45.1 (44.3)
5	8.5 (8.2)	17.2 (17.1)	26.7 (26.8)	43.7 (43.9)	55.1 (55.7)
10	10.0 (10.0)	20.4 (21.1)	31.4 (32.3)	50.6 (51.1)	63.1 (64.0)
100	16.7 (16.1)	34.8 (35.1)	52.3 (52.0)	79.8 (79.5)	96.3 (96.0)
1000	27.6 (25.9)	58.8 (58.5)	86.3 (83.6)	125.0 (123.8)	145.9 (144.0)
Estimated max.	60 (59)	134 (133)	190 (189)	249 (248)	270 (268)

An example of the application of this program for a location in North Wales specified by National Grid Reference SH 856407 (altitude 260 metres) is covered by the figures for Bala in Table VIII, but only a limited selection of values is given. Table IX shows the results obtained for the Catchment area of the Wansbeck River, Northumbria, and for comparison also gives the manually derived results as presented in *FSR*(2). The program can also output rainfalls in units of millimetres per hour for all durations up to 120 minutes. The latter are particularly useful for designing storm water drainage schemes in urban areas.

3.2. Computed storm profiles for durations ¼, ½, 1 and 2 hours are presented in Figure 4 for the same location in North Wales as the figures in Table VIII refer to. The *Road Note* 35 (RRL, 1963) 2-hour storm profile for the same 2-year period is also shown in Figure 3 for comparison.

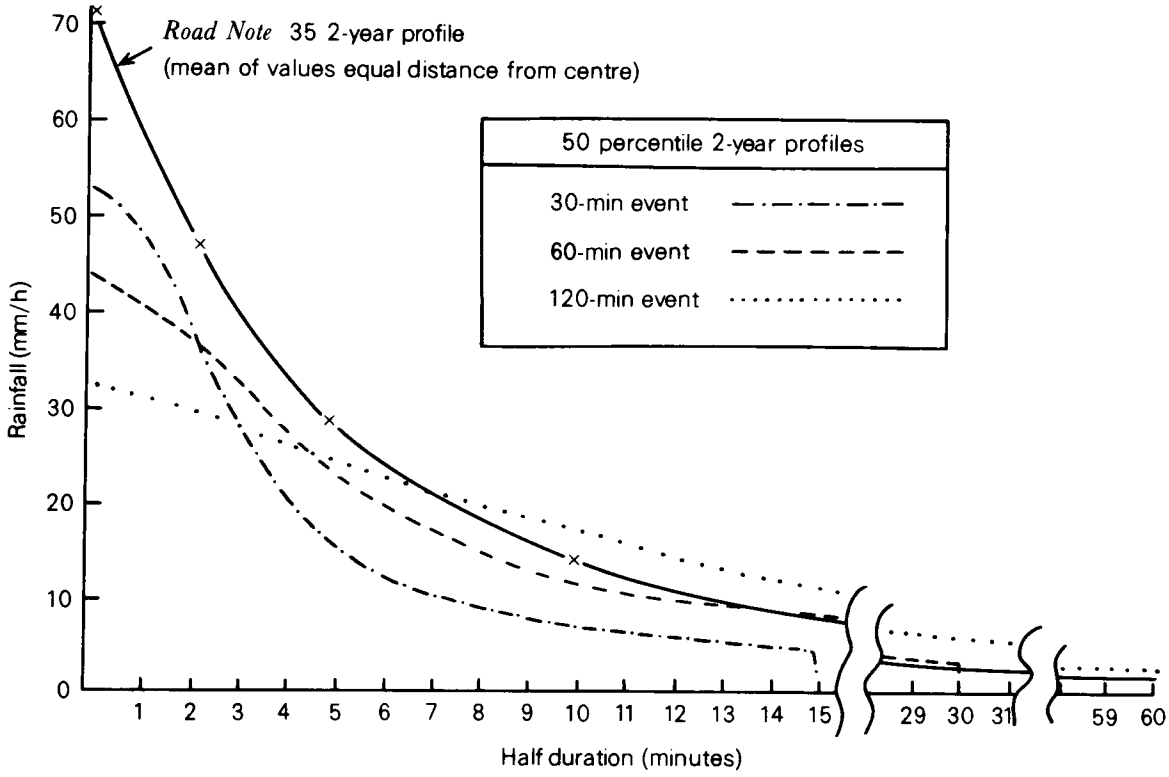

FIGURE 4. *Comparison of storm profiles of return period 2 years for different durations*

3.3. *Determining the return period of observed rainfalls*

The computer model can be used to determine the return period of any point or areal rainfall event up to 25 days duration at any location in the United Kingdom (specified by the National Grid Reference), given the duration and depth of rainfall. For example, the outstanding rainfall event of 14 August 1975 of 169 millimetres of rainfall in a 2½-hour duration, measured at one rain-gauge at Hampstead, Greater London, was estimated to be a 20 000-year point rainfall event, i.e. it has a 1 in 20 000 chance of being reached or

exceeded at that particular rain-gauge location in a period of 1 year (this assumes that no major change occurs in the climate). The estimated 15-minute rainfall intensity of 122 mm/h at the peak of the storm activity is objectively estimated to be a 200-year event (Keers and Wescott, 1976). Keers and Wescott also concluded that the severe localized rainfall as it occurred at Hampstead could be expected to recur about once every 25 years on average somewhere in the Greater London area.

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Printed in England for Her Majesty's Stationery Office by Hobbs the Printers Ltd Southampton
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